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Intensive Utilization of Harvest Residues in Southern Pine Plantations: Quantities Available and Implications for Nutrient Budgets and Sustainable Site Productivity

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Abstract The rising costs and social concerns over fossil fuels have resulted in increased interest in and opportunities for biofuels. Biomass in the form of coarse woody residues remaining after traditional timber harvest in the southeastern USA is a potentially significant source of biomass for bioenergy. Questions remain regarding whether the removal of this material would constitute a sustainable silvicultural practice given the potential impact on soil nutrient cycling and other ecosystem functions. Our objective is to review existing studies to estimate quantities of residual materials on southern pine forests that may be available, potential nutrient removals, and potential replacement with fertilizer. Regionally, it is estimated that 32 million Mg year^{-1} of dry harvest residues may be available as a feedstock. At the stand level, between 50 and 85 Mg ha^{-1} of material is left on site after typical stem-only harvests, of which half could be removed using chippers at the landing. Based on these estimates, increase in midrotation fertilization rates of 45% to 60% may be needed on some sites to fully replace the nutrients from harvesting residues removed for bioenergy. Field experiments suggest that residue removals do not degrade forest productivity in many cases, but more data are needed to assess the effects of frequent removals (i.e., from short-rotation systems) over longer periods and identify sites that may be particularly sensitive to the practice. A benefit of developing markets for previously nonmerchantable materials may create incentives for improved forest management by landowners.

Keywords Harvest slash · Nutrient removal · Forest stands · Forest soils · Southern yellow pine

Abbreviations
LTSP Long-Term Soil Productivity program

Introduction

Harvesting operations in intensively managed pine plantations often leave considerable amounts of traditionally nonmerchantable residues (e.g., branches, foliage, noncrop species) on site. More intensive utilization of these materials as a source of biofuels is being considered in response to rising costs and availability issues surrounding the use of nonrenewable fossil fuels; more complete utilization and markets could also serve as incentives to reduce greenhouse gas emissions to the atmosphere (or bioenergy) [15, 36]. Among the advantages of biofuels and other bioenergy is that they are considered a carbon-neutral source of energy since they reflect carbon recently removed from the atmosphere so, unlike the case with fossil fuels, no new carbon is introduced to the atmosphere [20, 63]. This is particularly attractive when using a waste product such as residues from traditional forest operations, especially since many are questioning the feasibility of other bioenergy from crops such as corn (*Zea mays* L.) [16, 50]. It has been estimated that recovering 70% of harvest residues could

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offset 17.6 million tons of carbon from fossil fuels in the USA or about 3% of the total US emissions for electricity in 1997 [21].

There is a wealth of prior work concerning the use of harvest residues for energy, particularly in the early 1980s [37]. Presently, biomass provides a considerable proportion of the energy used in some regions of the world [52]. In the past, bioenergy has generally been considered a less attractive energy option for more developed countries due to the low costs of fossil fuels. However, technologies for energy conversion have progressed significantly, and fuel costs have risen to the point that many of the previous assumptions about the economic viability of bioenergy may no longer be limiting.

Questions have been raised about potential effects of increased utilization of harvest residues and other forest biomass on sustainable forest productivity [41]. Today, timber-harvesting operations in pine plantations of the southeastern USA are typically highly mechanized systems that either transport the whole tree to the deck or remove the top at the stump. State best management practices often recommend redistributing nonmerchantable residues across the site to mitigate potential impacts on site nutrient removal and soil water retention, physical properties, and erosion that may affect future forest productivity [12, 56]. It is not clear, however, how more intensive residue removal influences these factors and subsequent productivity across a range of sites.

The objectives of this review are to (1) synthesize data on the quantities of harvest residues generated in pine plantations in the southeastern USA; (2) summarize the quantities of nutrients associated with intensive residue removal, the use of fertilizer to replace nutrient losses, and other mitigation practices; (3) review potential effects of residue removal on sustainable site productivity; and (4) identify knowledge gaps concerning potential impacts and management mitigation options.

Quantities of Residues in Managed Pine Plantations

There are 90 million hectares of forest in the southern USA, of which 13–20 million hectares are considered intensively managed. Annually, 2.2 million hectares are harvested (clear-cut), and 0.5 million hectares are fertilized [9, 17, 71]. It is estimated that forest residues could provide 5.7×10^7 dry Mg year^{-1} of material available nationally and 3.2×10^7Mg year^{-1} regionally [44] (Table 1). Of the forestry/agricultural feedstock sources, forest residues represent approximately 13% of potential biomass nationally and 22% of potential biomass in the South. Milbrant [44] provides detailed data regarding biomass resource availability in the USA.

Table 1 Estimated quantities of agricultural and forestry feedstock sources in the USA and southern USA

Source	National Mg$_{dry}$ year^{-1} (millions)	South
Agricultural crops	157	27
Dedicated crops	145	43
Forest residues	57	32
Mill residues	80	42

At the stand level, 50 to 85 Mg ha^{-1} of dry weight biomass (comprised of foliage, branches, and forest floor materials) may be left on site after typical stem-only harvesting on pine plantations in the southeastern USA depending on the age of the stand and the harvest practices employed (Table 2). The majority of this material consists of branches from the crop species and nonmerchantable species but also includes foliage and materials from the previous forest floor. Although the complete recovery of this material is probably neither possible nor desirable, it still represents a significant amount of material. While raking systems exist, simultaneous harvesting is the most efficient manner to collect this material as it requires no specialized equipment and less energy and results in less trafficking. In a recent field trial where whole-tree harvesting was employed, about 8 to 40 Mg ha^{-1} of residues was collected for use as biomass fuel using a conventional harvesting system and additional chippers at the logging deck [73]. This amount of biomass compares favorably to other forest types. A mature mixed Appalachian hardwood stand may yield 20 to 35 Mg ha^{-1} of residues following a conventional stem-only harvest [42], whereas aspen (*Populus tremuloides* Mischx.) stands in Quebec may yield 21 Mg ha^{-1} [2]. However, in Scandinavian Scots pine (*Pinus sylvestris* L.) or spruce (*Picea* spp.) stands where residues are harvested, only 5 Mg ha^{-1} may be collected [59].

Quantities of Nutrients Removed

As with biomass, nutrient removals also depend on stand age and harvesting practices but are more heavily influenced by tree species and tree components (e.g., branch vs. foliage). Few detailed inventories of nutrient distributions for the various tree components of southern pine species are available [7, 65, 66]. In general, foliage and the forest floor contain a higher quantity of nutrients than other woody components (Table 3). Loblolly pine (*Pinus taeda* L.) allocates more biomass to branches and stem wood while slash pine allocates slightly more to bark and foliage [34]. It is difficult to draw inferences without knowing the specific

Table 2 Biomass allocations of pine stands, not including the main bole, that are potentially available for bioenergy

Stand	Foliage/litter	Branches/nonmerchantable wood	Forest floor	Total biomass		Comments	Citation
				Retained on site	Removed		
Bole-only harvest	Mg ha^{-1}						
Loblolly pine, South Carolina, 20–25 years	18	41	5.3			Preharvest estimate	[14]
	25	51		76		Topped in place	[11]
	24	40		64		Delimbing gate	[11]
Loblolly pine, Texas, 27 years	7	33	20	77		Topped in place	[7]
Loblolly pine, Louisiana	10	37	33	82		Topped in place	[7]
Slash pine hybrid, Australia, 29 years	2	27	20	51–74			[65]
Radiata pine, Australia, 37 years	12	39	32	52			[66]
Whole-tree harvest							
Loblolly pine, Texas, 27 years	7	33	20	50	20[a]	Topped at deck	[7]
Loblolly pine, Louisiana	10	37	33	57	31[a]	Topped in place	[7]
Slash pine, Georgia					9	WTH, pine only	[73]
Slash pine, Georgia					24	WTH, pine, and hardwood	[73]
Loblolly pine, GA, LA, MS, TX, 30–56 years					28	Some stands thinned	[64]
Radiata pine, Australia, 37 years	12		32	43	39		[66]

[a] Estimated

proportion of foliage, branches, and other materials. As a first approximation, the weighted composite in Table 3 could be used to estimate the proportion of residue biomass and nutrients. Assuming these values, removals would be 2.5–6.7 kg N Mg^{-1} of dry material, 0.2–0.5 kg P Mg^{-1} P, 0.8–2.7 kg K Mg^{-1}, and 2.1–4.6 kg Ca Mg^{-1} under that assumption. As an example, if 30-Mg residues are removed from a 19-year-old plantation, nutrient removals may be as high as 200 kg N ha^{-1} and 16 kg P ha^{-1} (Fig. 1), 66 kg K ha^{-1}, and 74 kg Ca ha^{-1}. Pye and Vitousek [58] similarly found that residues in windrows of loblolly pine plantations on a Piedmont site contained 254 kg N ha^{-1} and 61 kg P ha^{-1}.

Quantities of Fertilizer Required to Offset Losses

The expense of manufacturing nitrogen and phosphorus fertilizers is high relative to other nutrients, which have comparatively negligible application rates and costs [26, 45, 47]. Common fertilizer rates for southern pine stands in the USA are 28–56 kg P ha^{-1} at stand establishment (depending on P limitations), and 170–225 kg N ha^{-1} and 28 kg P ha^{-1} were applied within the first 8 years [18]. The benefits of midrotation applications of N last approximately 8–10 years at which point further fertilization may be warranted to maximize stand production. However, only 30% to 50% of applied fertilizers are generally utilized by crop trees [25].

Based on the data from Table 2, in order to fully replace N removed per our example (30-Mg residues from a 19-year-old plantation), it would require an additional 45% to 60% over the commonly applied, midrotation fertilization rates, and up to a 28% increase in P rates to replace the N and P removed for biofuel. However, given that nutrients are released by the materials that remain, the complete replacement of nutrients may not be immediately or completely necessary. For instance, 12% of N was released after 8 years of decay in radiata pine (*Pinus radiata* D. Don.) plantations in Australia [23].

It is ultimately difficult to predict the specific fertilization requirements due to factors such as site quality and crop genetics [35, 43]. Areas with high nutrient availability generally have rapid growth and nutrient turnover but also higher nutrient exports [8]. These more productive sites are generally thought to be more resilient to harvesting disturbance than less productive sites [4, 61, 64], at least from a fertility standpoint [13]. Finally, the variability in nutritional demands between species, as well as the

Table 3 Nutrient quantities in dried southern yellow pine residue components from three studies [7, 65, 67]

Location/species	Foliage	Branches	Forest floor	Noncrop species	Weighted composite (foliage + branches)
Biomass (Mg ha^{-1})					
Louisiana (loblolly)	10	15	33	18	25
Texas (loblolly)	7	11	20	11	18
Australia (slash)	2	23	20	–	25
Australia (radiata)	12	39	32	–	51
N (kg Mg^{-1})					
Louisiana (loblolly)	12	3	10	2	7
Texas (loblolly)	13	3	6	2	7
Australia (slash)	8	2	5	–	3
Australia (radiata)	11	3	15	–	5
P (kg Mg^{-1})					
Louisiana (loblolly)	1.0	0.2	0.3	0.1	0.5
Texas (loblolly)	0.8	0.2	0.2	0.1	0.4
Australia (slash)	0.6	0.2	0.2	–	0.2
Australia (radiata)	1.1	0.3	1.0	–	0.5
K (kg Mg^{-1})					
Louisiana (loblolly)	3.5	1.3	0.7	1.1	2.2
Texas (loblolly)	3.7	1.2	0.5	1.3	2.1
Australia (slash)	2.0	0.7	0.2	–	0.8
Australia (radiata)	4.9	2.0	1.7	–	2.7
Ca (kg Mg^{-1})					
Louisiana (loblolly)	2.1	2.7	6.8	4.9	2.5
Texas (loblolly)	2.2	2.0	5.1	6.0	2.1
Australia (slash)	3.8	3.0	4.2	–	3.0
Australia (radiata)	7.1	3.8	13.5	–	4.6
Mg (kg Mg^{-1})					
Louisiana (loblolly)	1.1	0.7	1.1	0.5	0.8
Texas (loblolly)	1.2	0.7	1.0	0.7	0.9
Australia (slash)	2.0	0.8	1.0	–	0.9
Australia (radiata)	–	–	–	–	–

Loblolly pine (*Pinus taeda* L.), radiata pine (*Pinus radiata* D. Don), slash pine (*Pinus elliottii* Engelm.)

improvement among tree families [35, 76], indicates that fertilization requirements could be difficult to generalize. Foliar N and P critical levels are generally considered 1.2% and 0.1%, respectively [34]. King et al. [35] found fertilizer responses to vary greatly between even closely related families with some showing significant foliar growth enhancement at foliar N levels well above 1.2%.

Evidence for Effects of Residue Removal on Forest Productivity

Forest practices that repeatedly remove residues without replacing the nutrients and organic matter lost to harvesting have the potential to reduce long-term site productivity. The classic example for this is the decline in forest productivity in German forests resulting from forest floor removal, which demonstrated the importance of the litter layer for maintaining soil nutrient cycles and fertility [10]. Agricultural studies provide additional evidence that indiscriminate removal of residues can degrade soil physical, chemical, and biological properties [39]. Long-term field experiments also reveal that the importance of residue retention varies substantially with soil texture and other site characteristics [72].

Extensive information is available on the effects of southern pine postharvest site preparation practices including residue removal. Studies over the last three decades show that practices such as windrowing and shear-pile-disk can displace large quantities of nutrients and organic matter and have potentially detrimental effects on site productivity [19, 46, 48]. The relevance of these studies for assessing

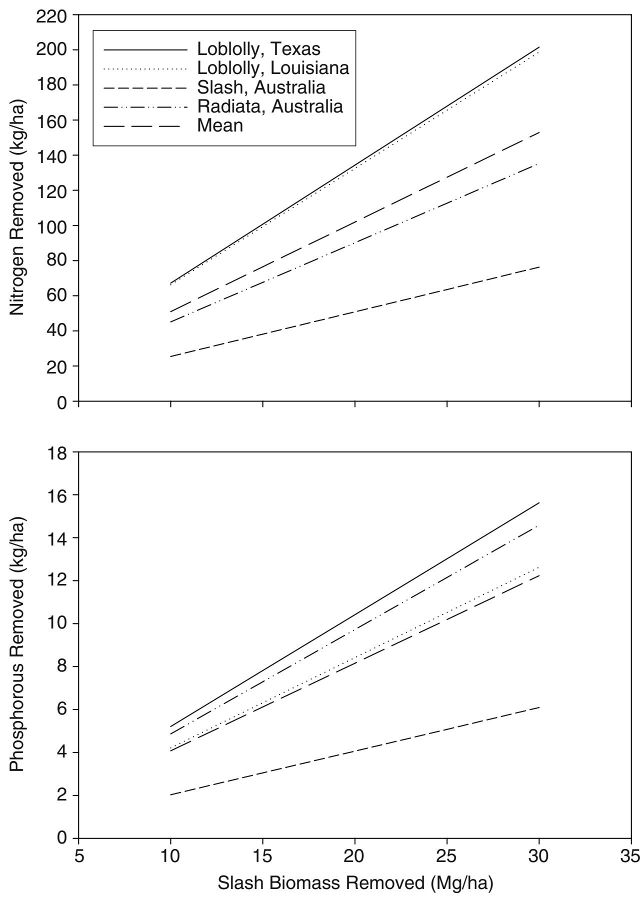

Fig. 1 Estimated absolute removals of nitrogen and phosphorous relative to dry residue biomass removals. Sites include loblolly plantations from Texas and Louisiana [7], a slash hybrid plantation from Australia [65], and a radiata pine plantation from Australia [67]

residue removal alone is limited, however, due to their confounding effects of soil displacement (i.e., removing nutrients and organic matter) and effects on competing vegetation, nutrient availability, and soil moisture [12, 48, 49, 55].

Harvest intensity studies (e.g., stem-only vs. whole-tree harvest) provide better insights into the effects of intensive residue removals. These studies have shown site productivity to be generally resilient but reveal that responses vary greatly across sites [4, 17, 57]. A meta-analysis of studies across a wide range of sites found no overall effects of harvesting on soil C and N levels and a trend toward slightly reduced soil C and N following whole-tree harvesting [31]. However, there was a wide range in responses for individual studies. Process-level assessments and empirical organic matter addition/removal studies both suggest a generally positive relationship between soil organic matter and forest productivity, but the relationship is complex and dependent on what site factors are limiting [22, 27]. For instance, in southern pine stands, soil organic matter has been linked to productivity and particularly on coarse-textured soils [12].

The largest study network evaluating the effects of residue removal and retention on site productivity is the North American Long-Term Soil Productivity (LTSP) program. A synthesis of findings for 26 of the oldest LTSP installations has found no overall effects of biomass removal on subsequent forest growth over 10 years [56]. They reported that forest floor removal but not residue removal reduced soil C concentrations but had little effect on total C mass. Forest floor removal also reduced soil N availability on some sites. Consistent with the national findings, LTSP loblolly pine installations in North Carolina and Louisiana showed no effect of organic matter removal on pine stand volume after 10 years but reduced extractable soil P [61]. By contrast, an analysis of LTSP installations and a similar experiment in the Gulf Coastal Plain of the southeastern USA (Louisiana, Mississippi, Texas, and Georgia) showed an 18% average reduction in tree growth after 7 to 10 years on 15 of 19 blocks when treetops were also removed [64]. It is important to note that with one exception these experiments did not include fertilizer application, which is a common practice in commercial forest stands on nutrient-limited sites. At the site where N + P fertilizer was applied to the whole-tree harvest treatment, productivity was 47% above that in the stem-only harvest treatment, suggesting that fertilizer may mitigate any productivity loss due to residue removal at that particular site and stage of stand development.

Knowledge Gaps

It is generally assumed that less productive sites low in soil organic matter and nutrient capital are more susceptible to productivity loss from intensive silvicultural practices [5, 54, 75], which could include intensive biomass removal. However, additional field evidence is needed to support this hypothesis. One residue management study across a forest site fertility gradient in New Zealand showed negative effects of residue removal on radiata pine growth lasting more than 4 years only on a sandy site at the low end of the fertility spectrum [69]. Harvest residues have been shown to reduce nitrogen leaching on sandy soils under radiata pine stands [6]. In the Gulf Coastal Plain LTSP study cited above [64], it was concluded that sites with low P availability were the most susceptible to intensive residue removal, although the greatest reductions in productivity were on sites with the highest site index.

In Denmark, whole-tree harvest of a Norway spruce (*Picea abies* L.) stand reduced stand growth on nutrient-poor sandy soils by up to 18% during the first 4 years, but the effect was not significant over the following 6 years or over the 10 years as a whole [51]. Boreal forest productivity model simulations suggested that growth reductions resulting from whole-tree harvesting would be highest on the most productive stands [53].

In addition to direct nutrient removal, other factors can influence tree and site responses to intensive harvesting. A comparison of sawlog, whole-tree, and complete-tree (including stumps) harvesting across four pine and deciduous forest sites in Tennessee, South Carolina, Florida, and North Carolina found variable effects on forest growth over 15 years [32]. There was no treatment effect on a mixed deciduous stand in Tennessee while whole-tree harvest reduced loblolly pine growth in South Carolina, which was attributed to reduced N retention and negative effects on soil physical properties where residues were absent. By contrast, complete-tree harvest increased forest biomass at the Florida longleaf pine site, likely the result of reductions in competing vegetation. Another assessment across 11 US sites reported greater nutrient removals from whole-tree than sawlog harvest, with calcium as the nutrient most susceptible to loss [40]. Lower initial growth rates on two of three whole-tree harvest sites that included both treatments could not be attributed to nutrient removals but were likely due to treatment effects on other factors such as herbaceous competition and microclimate.

One factor influencing the role of residues in sustaining site productivity is their residence time on the site. Over 80% of residue biomass decomposed over the first 15 years following whole-tree harvest of a Tennessee mixed oak forest [33]. In this case, residue retention enhanced foliar Ca, Mg, and K but had no effect on soil C. Due to their relatively rapid decomposition, residues may be less important for site productivity in southern (e.g., warm-temperate) forests compared to forests in colder climates. The degree of ground contact also influences residue decomposition rates. Decomposition of loblolly pine harvest residues that were in contact with the ground was 50% greater than residues without such contact [1]. Residues remained a net sink of N and P over at least 11 years following their deposition, although a large portion of K, Ca, and Mg was released during the initial 5 to 6 years following harvest.

Evidence from these studies suggests that residue removal associated with whole-tree harvesting has the potential to deplete site nutrients and productivity but that most forest sites examined appear resilient to the practice. There is little evidence that productivity declines cannot be corrected. Scandinavian societies have depended on intensive harvesting for decades to provide fuel wood; these practices provide examples of a scientific and philosophical approach to sustaining site nutrient capital and productivity by recycling and replenishing nutrients removed. Studies in that region show that nutrient removals due to whole-tree harvesting are often small compared to site reserves but can deplete soil base cations and other nutrients and reduce forest productivity on some sites. However, these depletions can also be corrected by identifying and replacing nutrients using wood ash and fertilizers [3, 30, 70, 74, 75].

Ultimately, the effects of repeated residue removals over long periods remain poorly documented for forests in the southern USA, which limits the conclusions that can be drawn about the sustainability of short-rotation biomass production systems. Findings from long-term agricultural experiments, which have repeated residue removals over decades, demonstrate that sustainability is feasible as long as limiting site factors are identified and corrected. These findings are consistent with those from intensive harvest studies in Scandinavia. One of the few examples of repeated residue removals in forest systems we reviewed found that productivity of willow (*Salix* L.) and hybrid poplar (*Populus alba* L.) plantations in central New York could be sustained over 10 years of annual harvesting when fertilization and irrigation were used [38]. Although important questions remain, the weight of evidence from a range of studies suggests that the logical solution for sustaining forest productivity under repeated residue removal will be to identify sensitive sites and develop nutrient replacement regimes that avoid or mitigate deficiencies. This will require both a scientific understanding of limiting site factors and the flexibility to address them.

Considerations for Implementation of Residue Collection

Forests in the USA are not the most intensively managed in the world. Experience in other parts of the world suggests that increased management intensity will likely require more sophisticated prescriptions and evaluation [18, 68], particularly with regards to maintaining nutrient budgets. Fertilization is expensive and prices for nitrogen have more than quadrupled in the past few years. Conservative strategies sacrifice maximum yield, while more aggressive regimes are costly and can negatively impact water quality [25]. Stand-level management may need to be better integrated at landscape scale with greater consideration given to appropriate rotations and species selection [39, 63]. More detailed stand records may be required to allow for crop history tracking [27]. However, fertilization costs to correct nutrient removals could be offset by the revenues generated from the sale of the residues. In the case of conventional fertilization, fertilization costs are an investment offset by the future sale of biomass and affected by future market uncertainties.

Traditionally, several technological and economic hurdles have prevented widespread utilization of forest biomass for energy in the USA. Energy from biomass remains a relatively expensive source compared to fossil fuels, hydropower, and wind [62]. Biomass accounts for only 3–4% of the total energy consumption in the USA mostly in the industrial sector using waste products [24]. The amount of space required for the storage and transport of biomass chips is three to four times for an energy equivalent amount of coal or 11–15 times that of oil, and thus transportation costs are high [24, 28]. It has never been economically feasible to transport logging residues at great distances [21]; therefore, wood-derived power seems to favor small or isolated markets or decentralized facilities.

At some point, technology may improve or markets may change such that the economic constraints of wood bioenergy can be overcome. At that time, socioeconomic factors may dictate the use of harvest residue as biofuel. Potential negative impacts such as nutrient loss, soil erosion, and decreased organic content are obvious concerns. However, there are potential benefits as well. For example, an increased market value for residue could diminish practices such as "high grading" which create lower-quality forests [60]. Increasing the profitability of midrotation thinning operations in pine stands (particularly from below) and improvement cutting in hardwood stands may also improve carbon sequestration rates, improve stand quality, and increase overall volume [29]. Additionally, improved silvicultural systems may also be developed for degraded and marginal lands including mined lands [39].

Conclusions

As much as 50 to 85 Mg ha^{-1} (dry) of harvesting residues remains on the surface after a harvesting operation on an industrial southern yellow pine plantation. This material is comprised of limbs and foliage from the tops of the harvested trees and material from the previous forest floor. Approximately 10 to 40 Mg ha^{-1} dry material (20 to 80 Mg ha^{-1} wet) could be collected for biofuel if simultaneously collected during a conventional harvesting operation with the addition of a chipper. Current markets classify this material as "hog fuel" and value it at \$16 to \$20 Mg^{-1} for undried material. Whether this practice is ultimately adopted will depend on improving the technology that converts these materials to energy, expanding and developing markets, and changes in societal perception and values.

One of the environmental costs of utilizing this material is the removal of nutrients that would otherwise serve as a nutrient source for future stands. Clearly, it is technologically feasible to use fertilizers as a means to offset these losses. Nitrogen and phosphorous are generally the most limiting and most expensive nutrients for sites in the southeastern USA. Up to 6.7 kg of nitrogen, 0.5 kg of phosphorous, and 2.7 kg of potassium may be removed for each megagram of residue harvested for biofuel. Whether there is a negative long-term effect from residue removal is unclear from the results of existing resources, and the effects are likely site dependent. Responses may be quite variable depending on the species (or clones) present and current nutrient status of the site, although more fertile sites are likely to be more resilient to the practice.

The use of these materials may require greater involvement and monitoring on the part of stand managers to be sustainable in the long term. Based on currently available information, it does not seem that there will be a negative long-term effect from residue removal as long as a forest floor remains intact. This seems particularly true for fertile sites and for sites that will receive fertilization.

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